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Prospects for Measuring $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ at BNL

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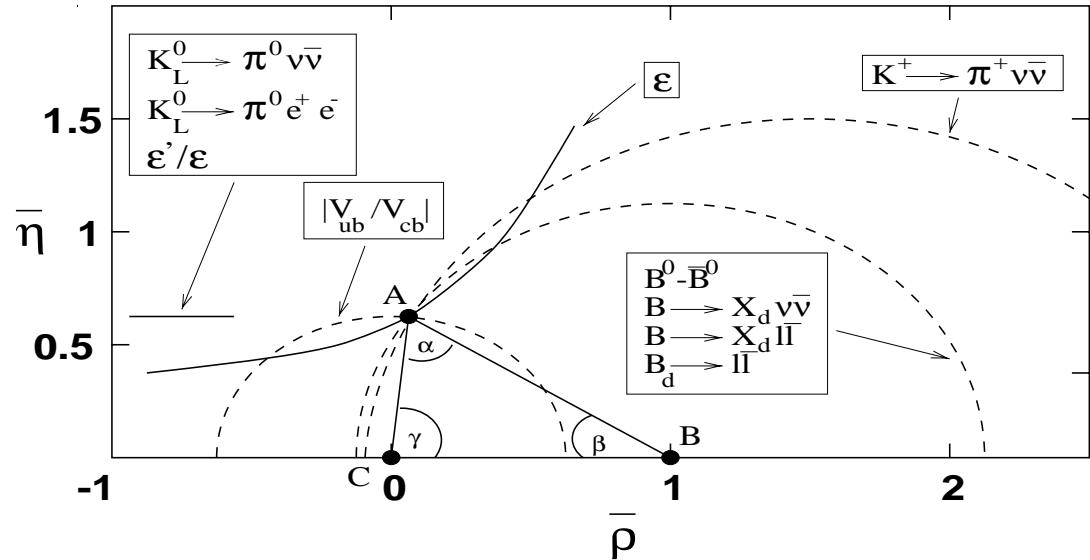
CP VIOLATION – one aspect of the “Generation Puzzle”.

$u \quad c \quad t \quad e \quad \mu \quad \tau$

$d \quad s \quad b \quad \nu_e \quad \nu_\mu \quad \nu_\tau$

- CP/T violation seen only in K decays.
Coming soon to B_s ?
- Lepton flavor violation may have shown up in neutrino oscillations implying possible CP violation in the lepton sector?

Unitarity relations e.g. $V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0$



Four "Super-clean" K and B physics inputs will test the SM CP-V picture. (Buras)

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

E787/E949 (BNL), CKM (FNAL)

$$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$$

KOPIO (BNL), KAMI (FNAL)

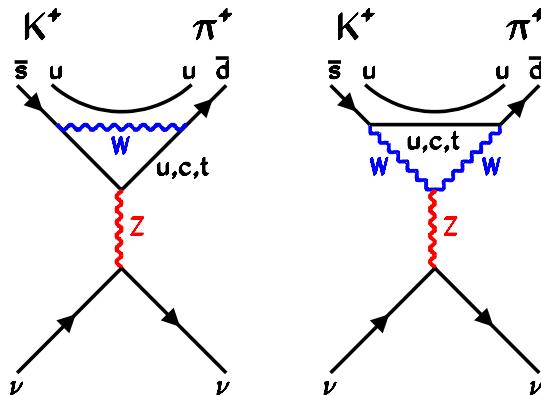
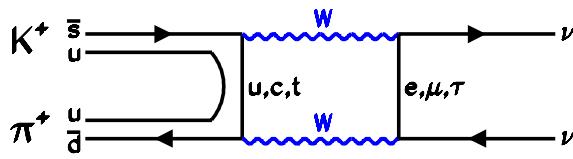
$$B_d \rightarrow \Psi K_s$$

BABAR, BELLE, CDF, HERA-B, et al.

$$\frac{x_s}{x_d} = \frac{B_s - \overline{B}_s}{B_d - \overline{B}_d}$$

LEP, SLD, LHCb, BTEV, et al.

$K \rightarrow \pi \nu \bar{\nu}$ in the Standard Model



	$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$
Top Dependence	$ \lambda_t = V_{ts}^* V_{td} $	$\text{Im}(\lambda_t) = \text{Im}(V_{ts}^* V_{td})$
Calc. BR (10^{-10})	0.82 ± 0.32	0.28 ± 0.1
Est. Theory Uncertainty	5% (charm)	2%

- Negligible long distance effects (10^{-13}).
- Hadronic matrix elements from isospin analog $K^+ \rightarrow \pi^0 e^+ \nu_e$.

E787 COLLABORATION

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E949

An experiment to measure the branching ratio $B(K^+ \rightarrow \pi^+ \nu\bar{\nu})$

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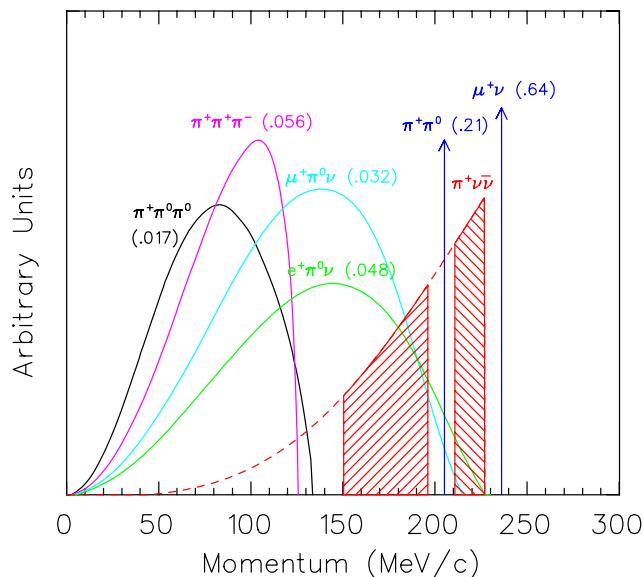
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Yeshiva University

E787: Measuring $K^+ \rightarrow \pi^+ \nu \bar{\nu}$



$K^+ \rightarrow$

π^+

$\nu \bar{\nu}$

Stopped $K \rightarrow \pi$

Momentum

4π Veto

C.M. system

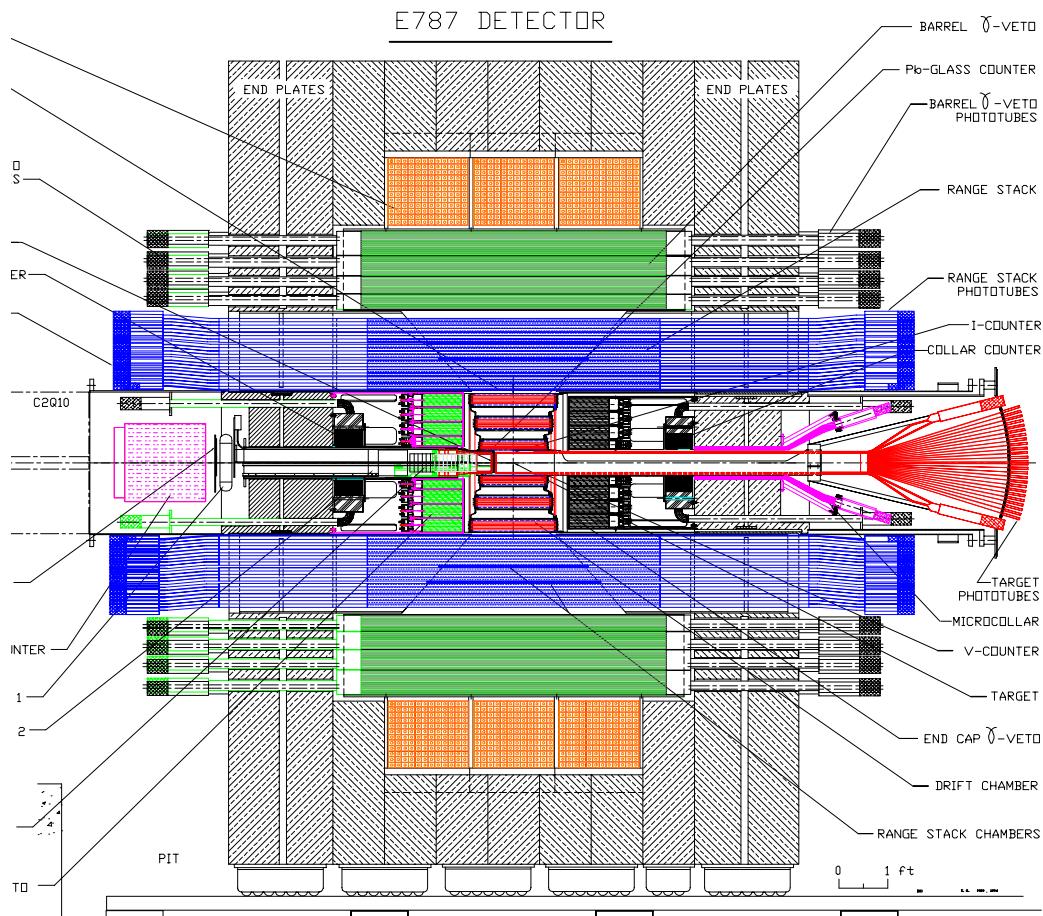
Energy

Range

$\pi \rightarrow \mu \rightarrow e$

PHILOSOPHY:

- Get as much information as possible!
- Suppress backgrounds ($K \rightarrow \pi^+ \pi^0$, $K^+ \rightarrow \mu^+ \nu$,)
S/N = 10.
- Perform “blind” analysis to avoid bias.



$K : \pi \sim 4 : 1 \rightarrow \check{C}_K \rightarrow \text{BeO degrader} \rightarrow$
active, segmented target

$\pi^+ \rightarrow 1.0 \text{ T drift chamber} \rightarrow$
21-layer, segmented range stack

photon veto: $14 X_0$ barrel, $13.5 X_0$ CsI endcap,
Pb glass, collars

data acquisition: $\sim 1.0 \times 10^6 K^+$ stops in target per 1.5-sec spill
 $\sim 200; K^+ \rightarrow \pi^+ \nu \bar{\nu}$ triggers per spill

Backgrounds

- K^+ -decay backgrounds suppressed via
 - kinematics: stopped K^+ beam, dE/dx , R vs. P
 - high efficiency photon detection
 - π^+/μ^+ particle ID: $\pi \rightarrow \mu \rightarrow e$ decay sequence
- non- K^+ -decay backgrounds suppressed via
 - high efficiency identification of beam K^+
 - non-coincident beam and track activity (“delayed coincidence”)

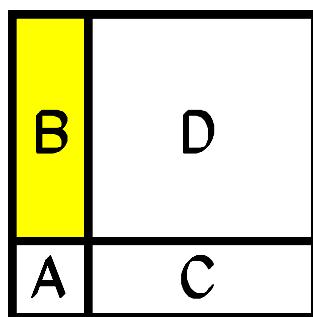
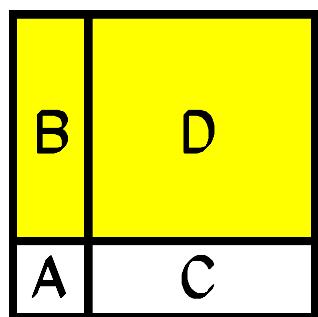
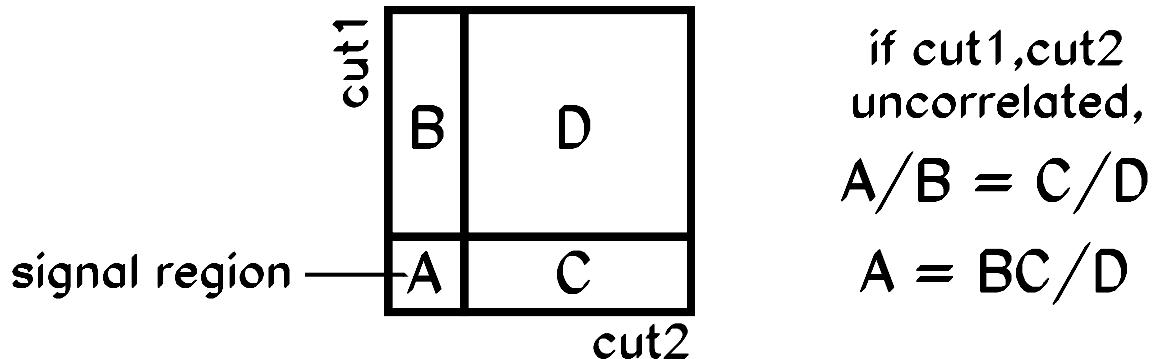
Background	BR	kin.	PV	PID	>1 tr.	$\check{c}_{K,\pi}$	DC
$K^+ \rightarrow \mu^+ \nu \mu$	0.64	✓		✓			
$K^+ \rightarrow \pi^+ \pi^0$	0.21	✓	✓				
$K^+ \rightarrow \pi^0 l^+ \nu_l$	0.08		✓	✓			
$K^+ \rightarrow 3\pi$	0.07	✓	✓		✓		
$K^+ \rightarrow \mu^+ \nu \mu \gamma$	5×10^{-3}	✓	✓	✓			
$K^+ \rightarrow \pi^+ \gamma \gamma$	1×10^{-6}		✓				
beam π^+						✓	✓
$K_L^0 \rightarrow \pi^+ l^- \bar{\nu}_l$					✓		✓

Analysis Strategy

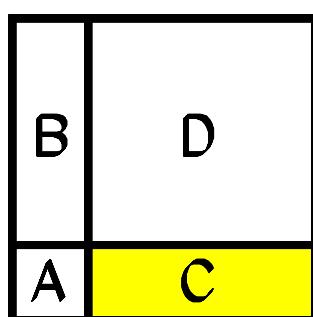
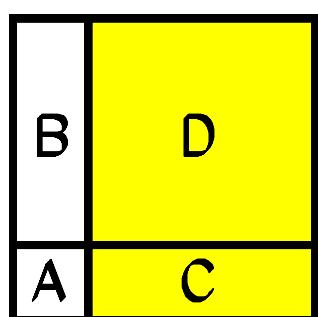
require $> 10^{10}$ suppression of backgrounds
→ **low statistics bias**

- **blind analysis**
 - identify background sources *a priori*
 - define a “box” where signal:background is highest
 - do not establish cuts by examining events in the box;
instead perform:
- **bifurcated analyses**
 - enhance statistics for background estimation
 - background samples isolated from the real data
 - where possible – all potential event pathologies are taken into account
 - perform outside-the-box tests of correlation in the bifurcations
- **test for bias on independent data samples**

Goal: expected background in box $\ll 1$ event, with rejection in reserve for evaluation of candidate events

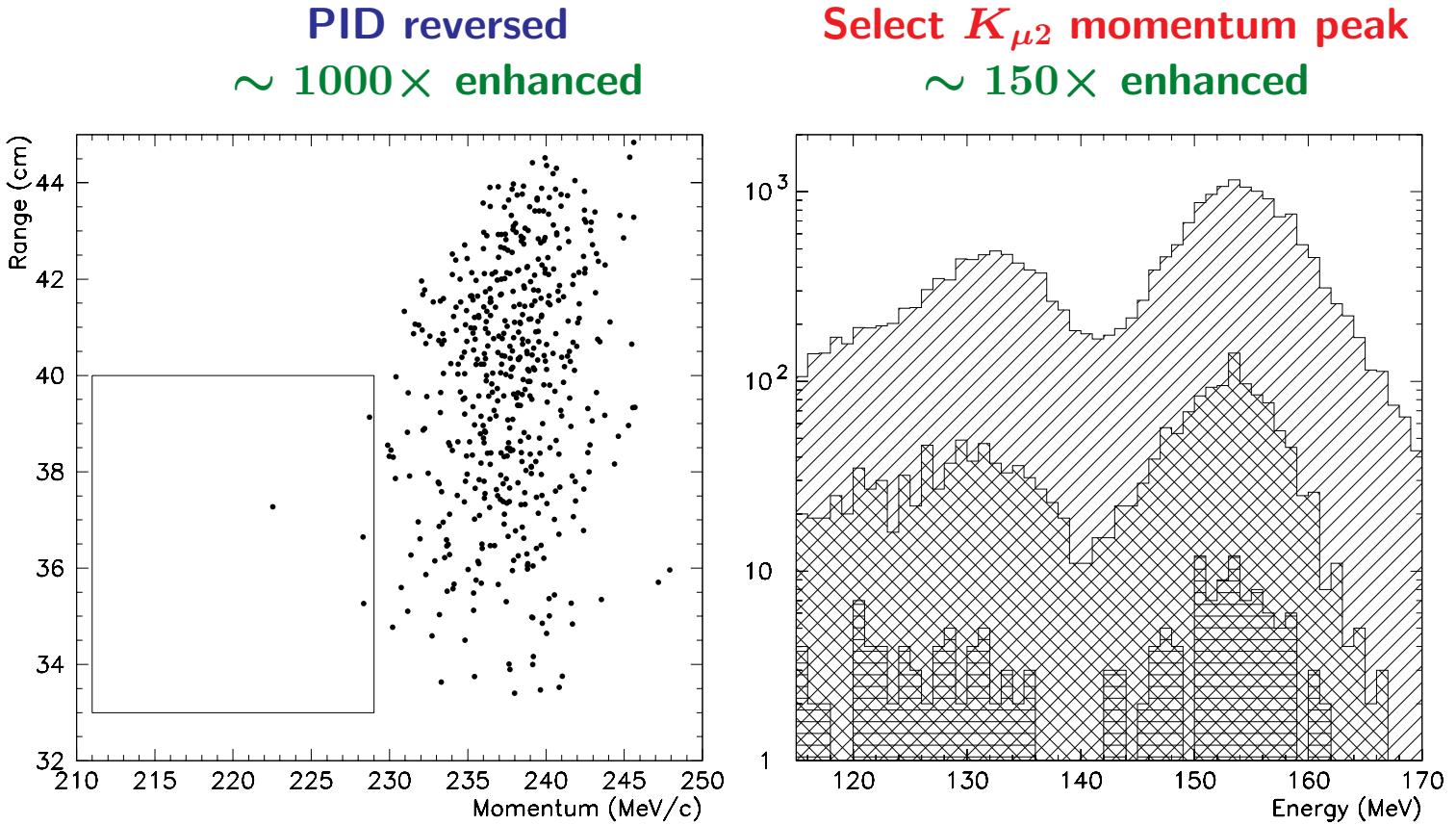


$$N = B$$



$$\text{bg} = N/(R-1) \\ = BC/D$$

Bifurcated Background Estimates



$$\text{Background} = \frac{N_{K_{\mu 2}}}{(R_{PID} - 1)}$$

Background	Normalization	Rejection
$K_{\pi 2}$	kinematics	photon veto
$K_{\mu 2}$	kinematics	PID $\pi \rightarrow \mu \rightarrow e$
single beam	$\check{C}_K, \check{C}_{\pi}$ time, B4 dE/dx	delayed coincidence
double beam	B4 time	BWC, $\check{C}_K, \check{C}_{\pi}$ time
charge exchange	K_S^0 data	Monte Carlo

Background Levels

Background	1995-7
$K_{\pi 2}$	0.022 ± 0.005
$K_{\mu 2}$	0.028 ± 0.010
BM1	0.005 ± 0.004
BM2	0.016 ± 0.015
CEX	0.010 ± 0.007
total	0.08 ± 0.02

“golden” region #1: 0.010 ± 0.003
background events
at 36% signal region acceptance

“golden” region #2: 0.006 ± 0.002
background events
at 33% signal region acceptance

Acceptance

	1995-7
K^+ stop efficiency	$0.704 \pm 0.004^{stat} \pm 0.009^{syst}$
K^+ decay after 2 ns	0.850 ± 0.001
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ phase space	$0.155 \pm 0.001^{stat} \pm 0.001^{syst}$
Solid angle acceptance	0.407 ± 0.001
π^+ nucl. int., decay-in-flight	0.513 ± 0.005^{stat}
Reconstruction efficiency	0.959 ± 0.001
Other kinematic constraints	$0.665 \pm 0.007^{stat} \pm 0.020^{syst}$
$\pi - \mu - e$ decay acceptance	$0.306 \pm 0.005^{stat} \pm 0.004^{syst}$
Beam and target analysis	0.699 ± 0.001
Accidental loss	0.785 ± 0.002
Total acceptance	$[0.208 \pm 0.005^{stat} \pm 0.021^{syst}] \%$

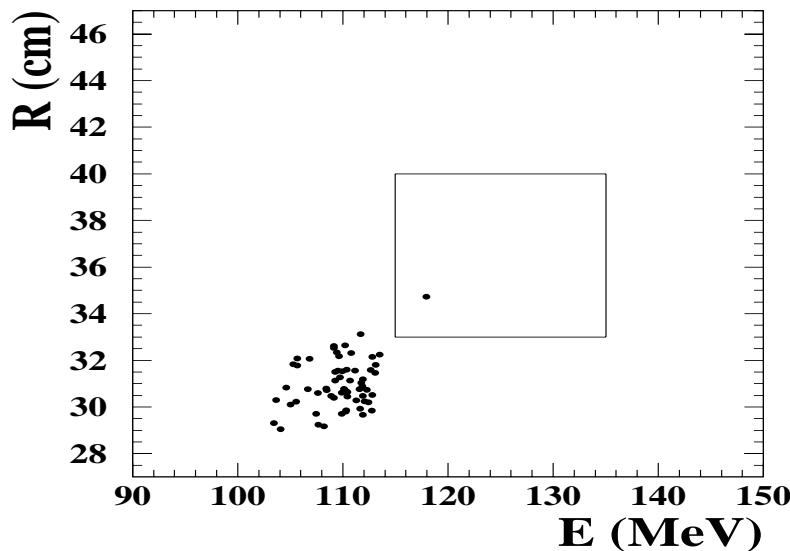
exposure: $3.24 \times 10^{12} K^+$
entered the target

Evidence for the Decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (E787)

1995-97 Data: One event observed.

Estimated background: $n_b = 0.08 \pm 0.02$.

$$N_K = 3.24 \times 10^{12} \text{ Acceptance} = 0.208 \pm 0.005(\text{stat}) \pm 0.021(\text{syst})$$



Results:

$$\mathcal{R}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = \frac{\Gamma(K^+ \rightarrow \pi^+ \nu \bar{\nu})}{\Gamma(K^+ \rightarrow \text{all})} = 1.5^{+3.4}_{-1.2} \times 10^{-10}$$

$$0.002 < |V_{td}| < 0.04$$

E787 → E949 at BNL

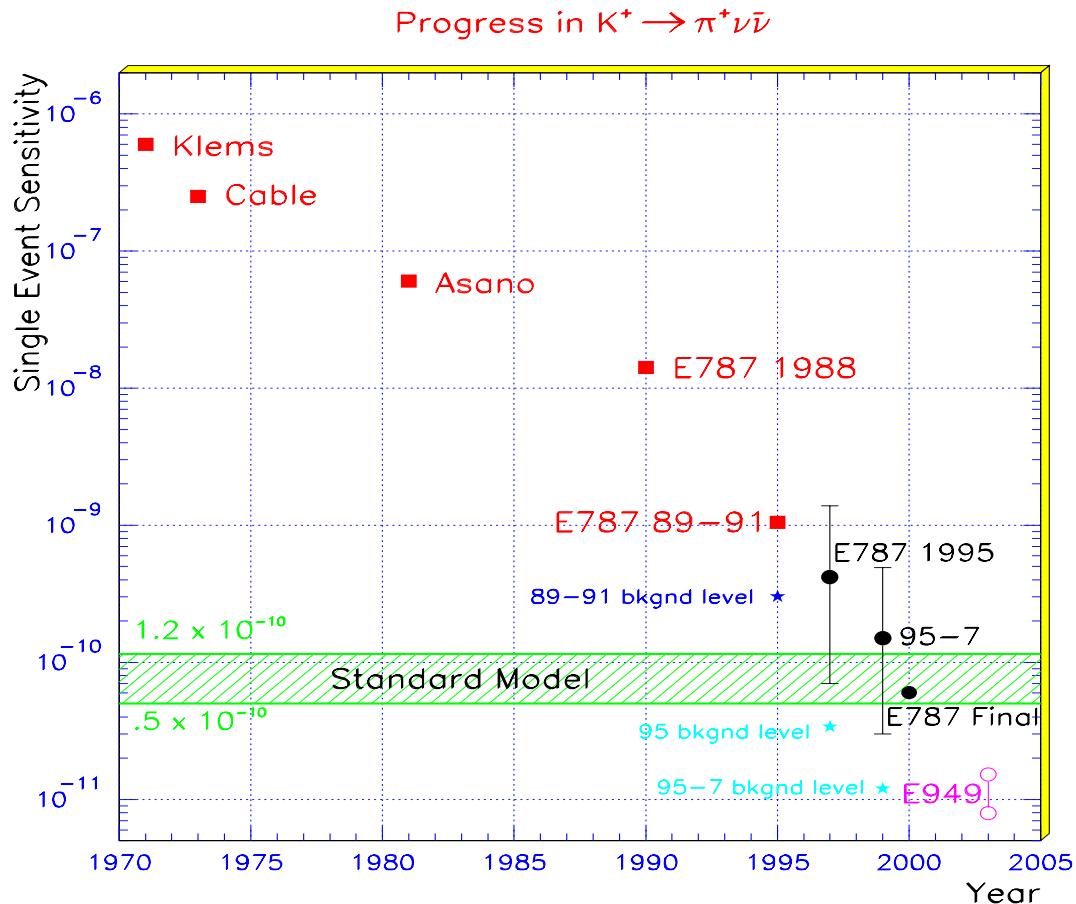
E949 GOAL (2000-2002):

$$K^+ \rightarrow \pi^+ \nu \bar{\nu} \text{ single-event sensitivity } (8 - 15) \times 10^{-12}$$

- More protons/spill on the K^+ production target (15 Tp/spill → > 65 Tp/spill)
- Increased spill length: instantaneous rate stays low and duty factor improves (41% → 64%)
- Lower K^+ beam momentum → higher K^+ stopping fraction (by ~ 38% over conditions in 1995)
- Improved data acquisition: smaller trigger and readout deadtimes and online accidental losses
- Improved photon detection efficiency, trigger-counter efficiency, and beam spatial resolution
- Longer running periods (\geq 25 weeks/year, symbiotic with RHIC)

Factor of 14 estimated increase in sensitivity/year (over 1995 conditions).

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ Progress



- Background in E787 95-97 data OK for measurement.
- E787 1998 data comparable in sensitivity to previous total.
- E787 now becomes E949 aiming for 5x sensitivity of E787. Running starts at the AGS in 2001.
- CKM proposal at FNAL aims for 10x greater sensitivity.

KOPIO Collaboration

E926 - Measurement of $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

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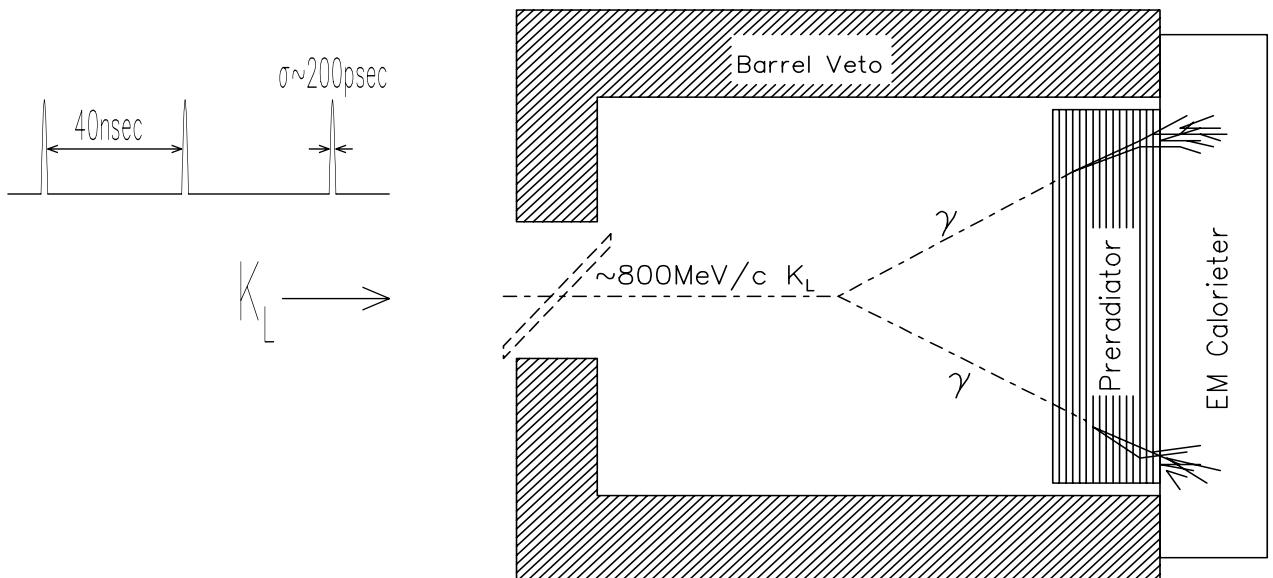
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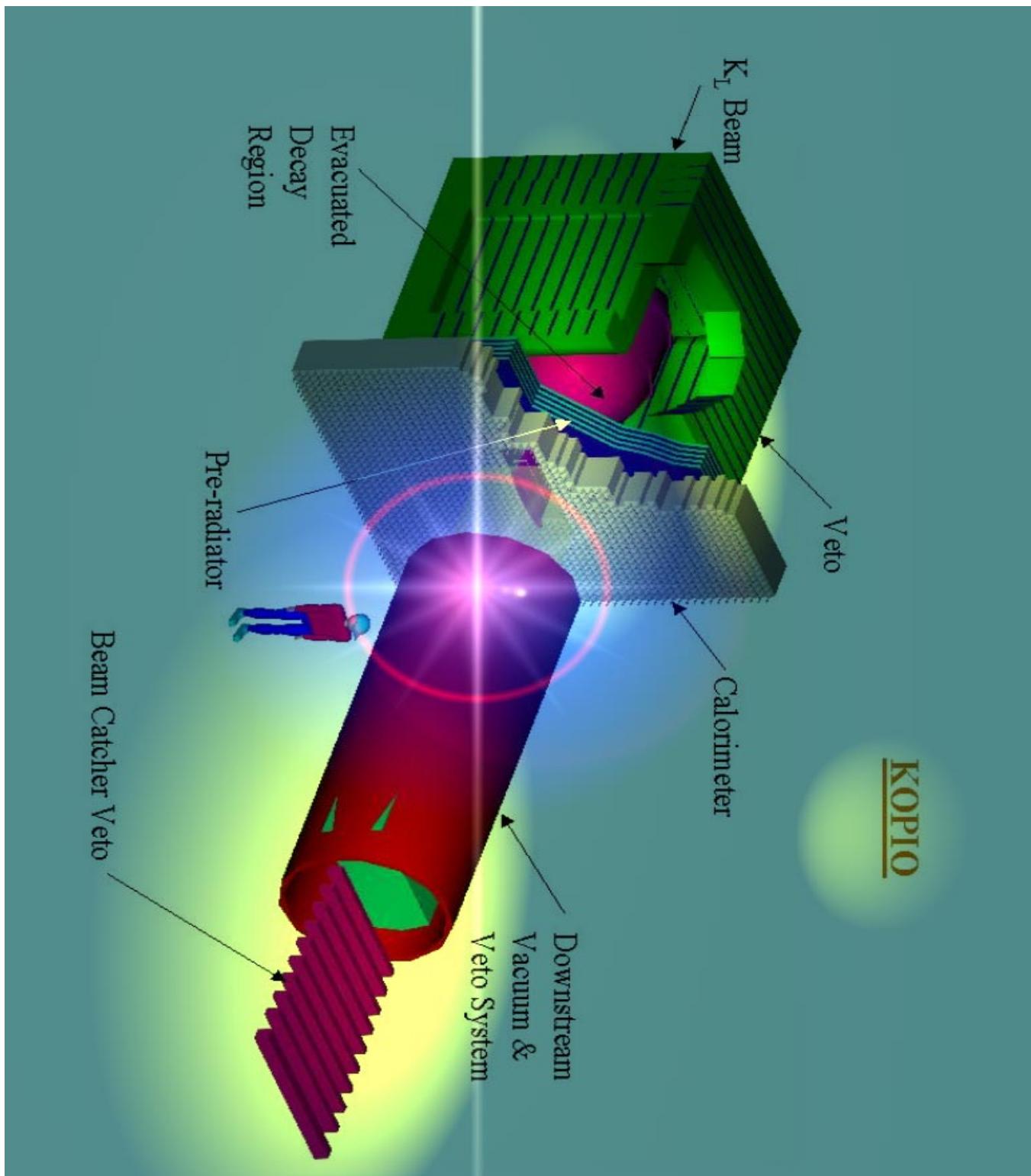
KOPIO: A Proposal to Measure $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

Lessons from E787:

- Measure as much as possible:
Energy, position and ANGLE of each photon.
- Work in the C.M. system :
Use TOF to get the K_L^0 momentum.
- Photon Veto limited by photonuclear interactions at low energies.



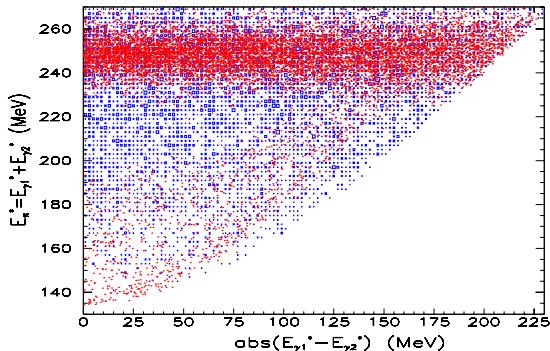
KOPIO



KOPIO: Challenges and Goals

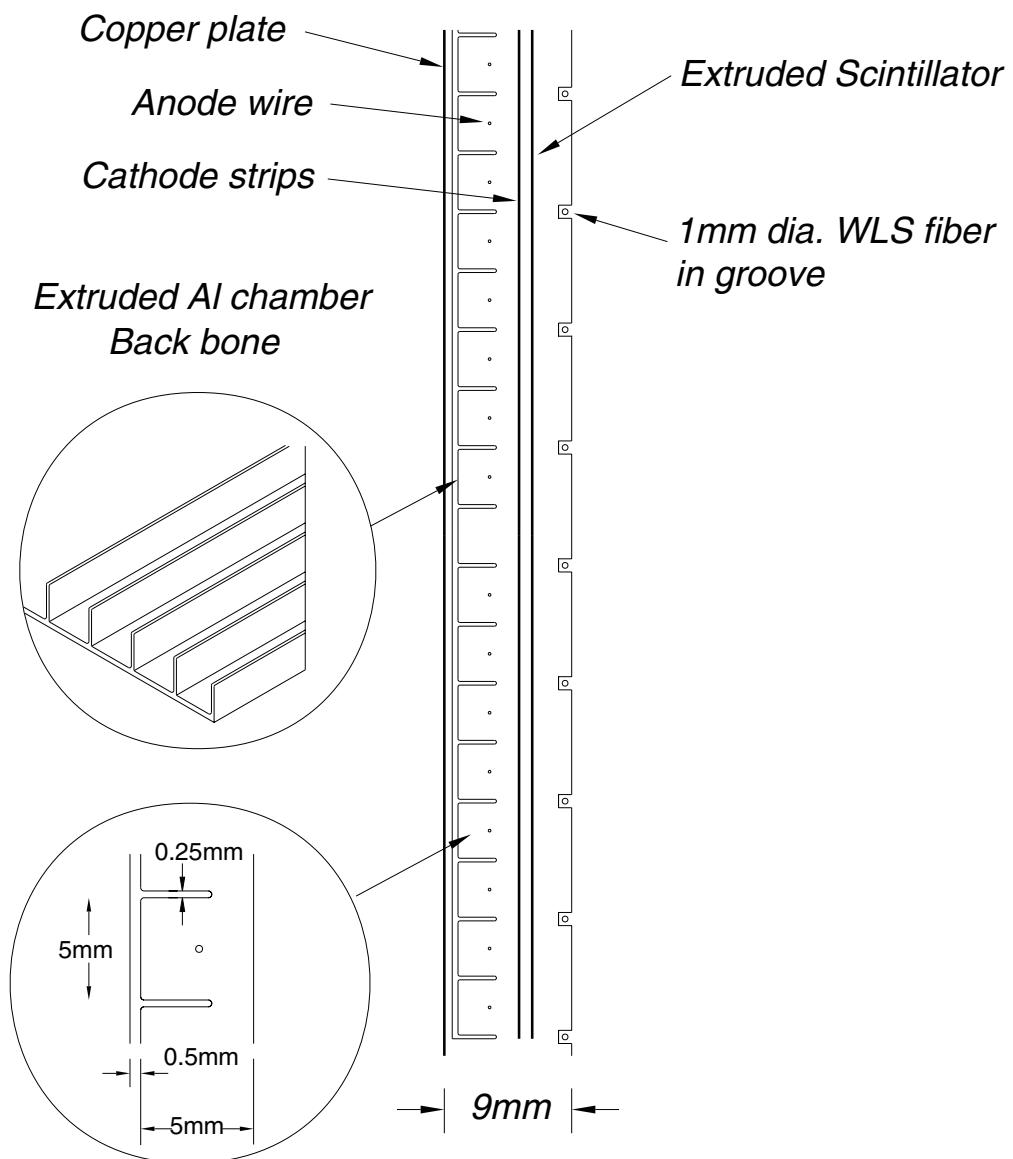
- Largest background source $K_L^0 \rightarrow \pi^0\pi^0$.
Weapons: Kinematic reconstruction, photon veto.
Eliminate events with missing low energy photons.
- Photon inefficiency : 10^{-4} at 200 MeV.
(Comparable to E787).
- Photon angular resolution : 17 mr at 350 MeV
(10 mr achieved by GLAST)
- Energy resolution : $\frac{3.5\%}{\sqrt{(E(GeV))}}$.
(Achievable with "Shashlik")

$$\begin{array}{c} \textcolor{red}{K_L^0 \rightarrow \pi^0\pi^0 \text{ Background}} \\ \hline E_{\pi^0}^* \text{ vs. } |E_{\gamma 1}^* - E_{\gamma 2}^*| \end{array}$$



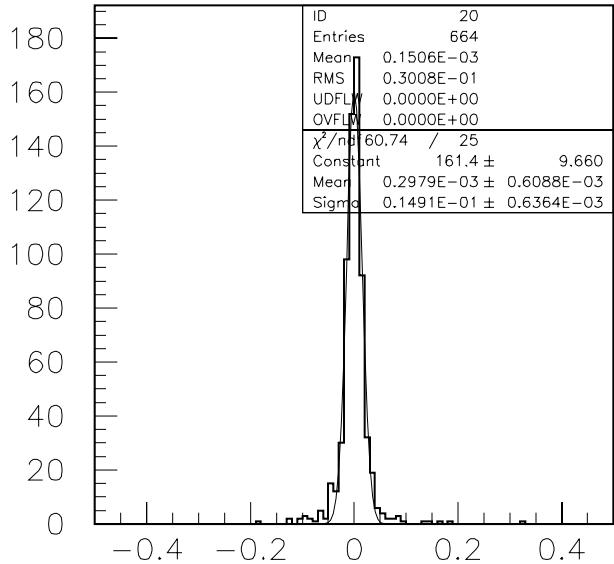
Using the 24 GeV AGS (between RHIC pulses), 10^{14} p/spill, expect 1.5×10^{14} K decays, and 60 $K^0 \rightarrow \pi^0 \nu\bar{\nu}$ events with S/N=2.

PRERADIATOR ELEMENT DESIGN

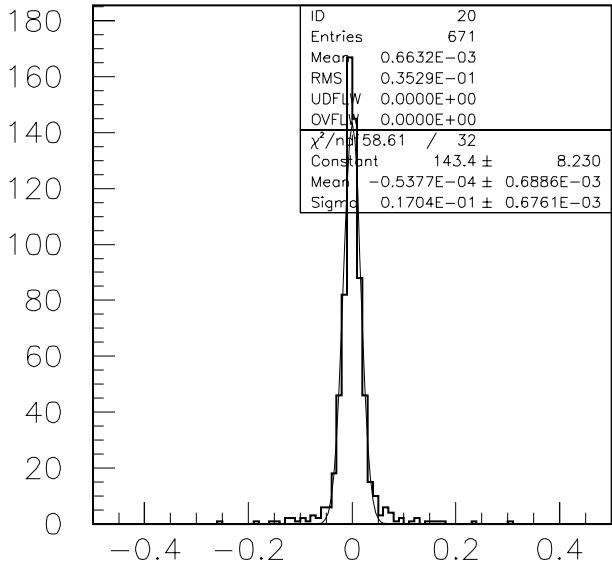


PRERADIATOR SIMULATION

m450xa.hbook

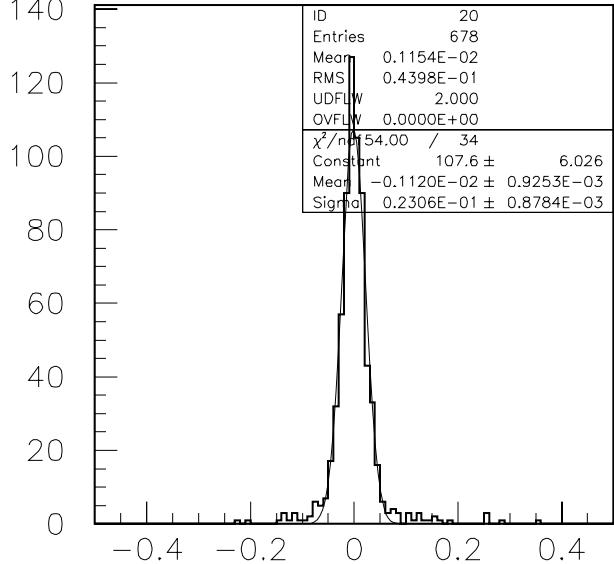


m350xa.hbook



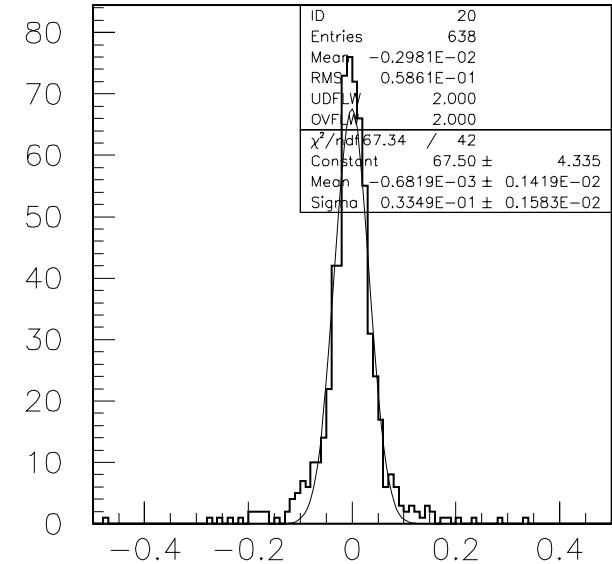
fitted x angle

m250xa.hbook



fitted x angle

m150xa.hbook

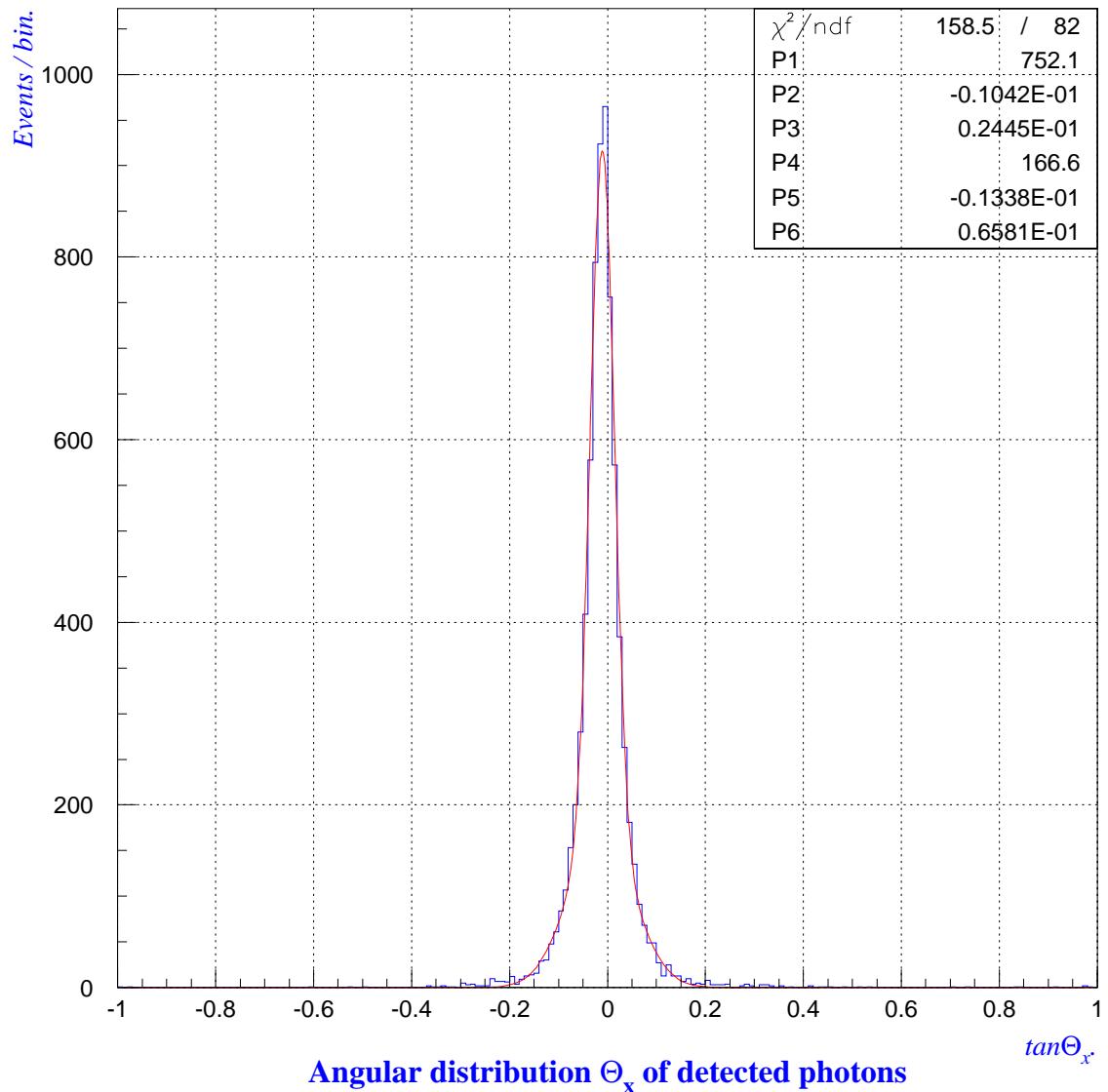


fitted x angle

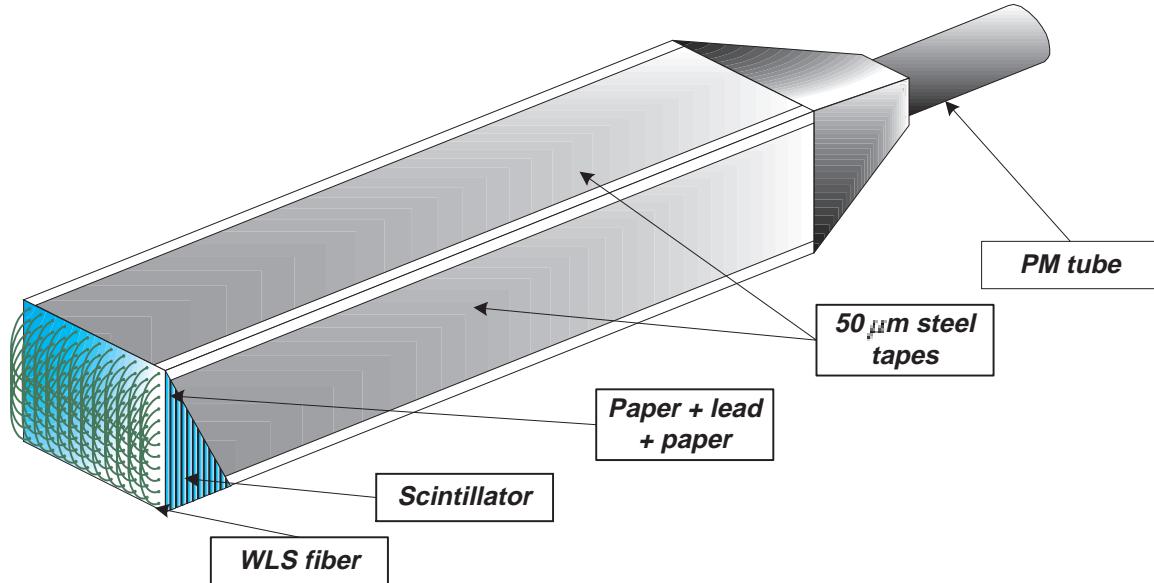
fitted x angle

Tagged Photon Test of Preradiator

KOPIO. Preradiator Prototype Test. Cathode readout.



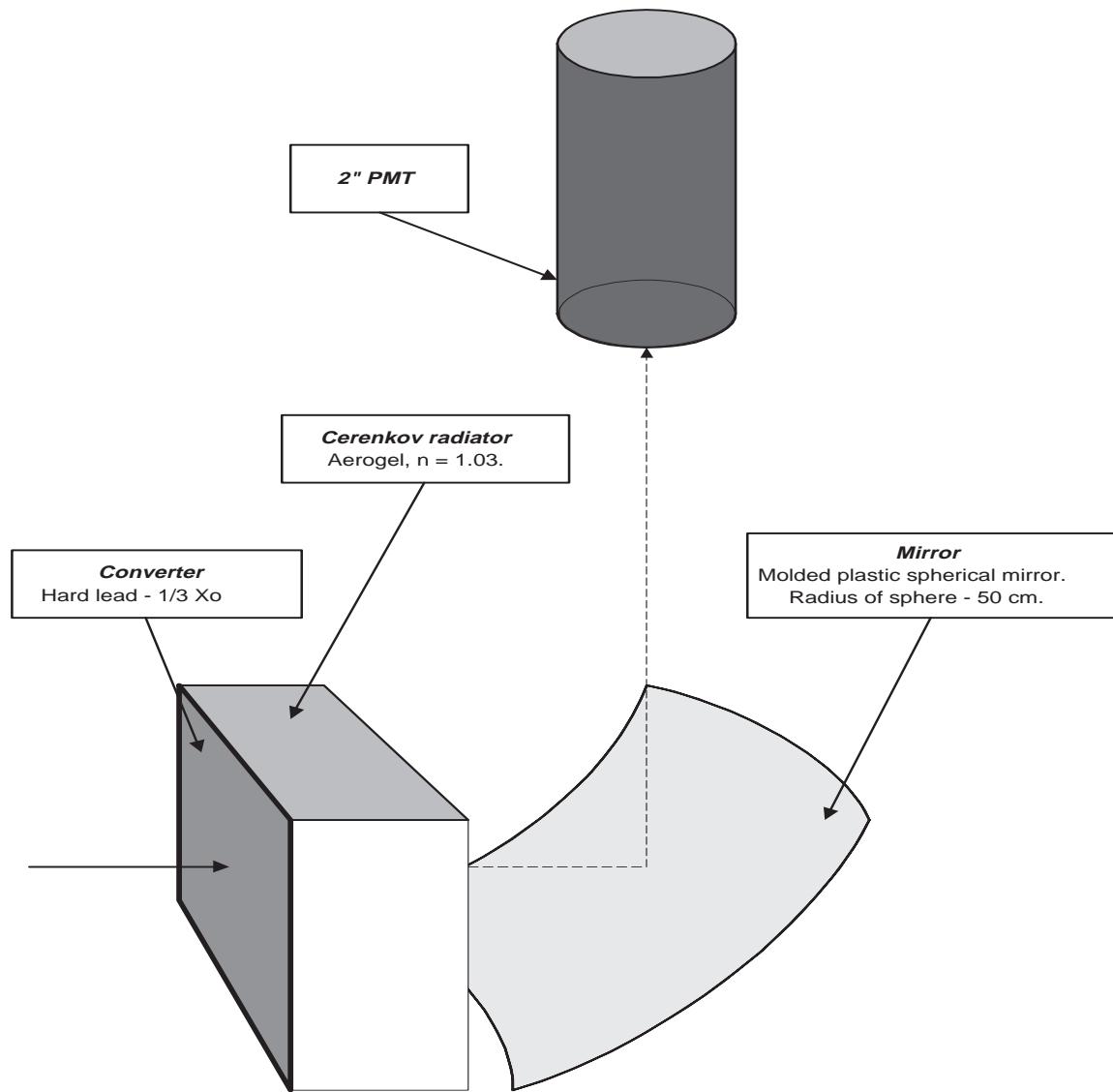
SHASHLIK CALORIMETER MODULE



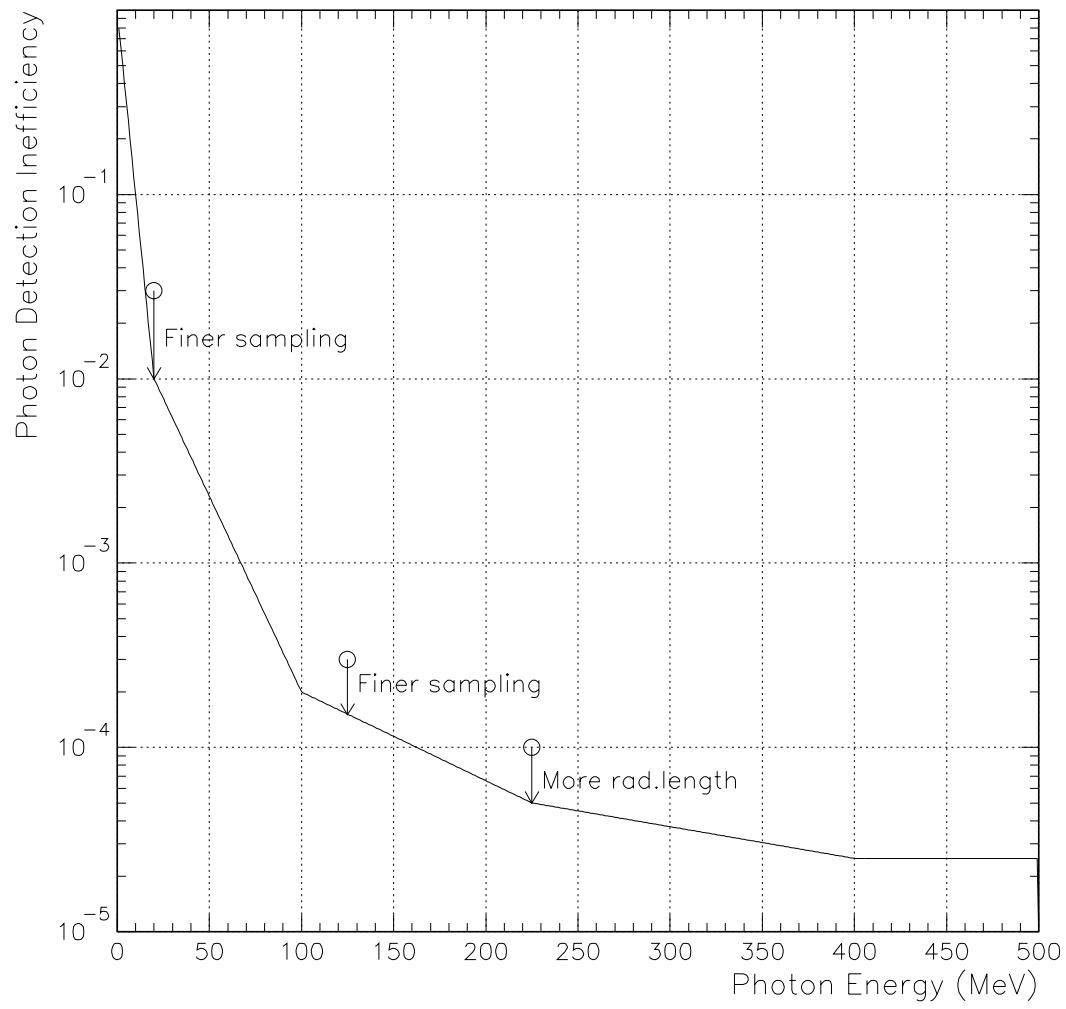
**Anticipated Energy
resolution:**

$$\frac{\Delta E}{E} = \frac{3.5\%}{\sqrt{(E(GeV)}}.$$

Beam Catcher Detector



Photon Detection Inefficiency

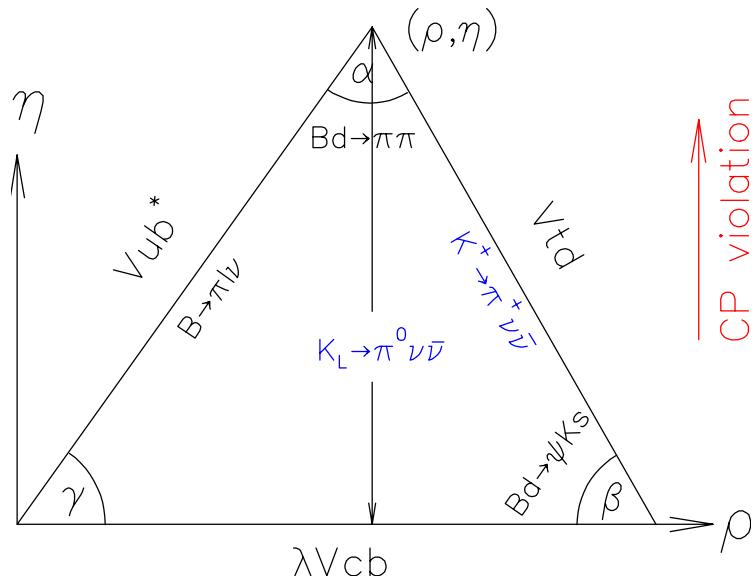


KOPIO Signal and Backgrounds

Process	Modes	Main source	Events
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$			65
K_L decays ($\bar{\gamma}$)	$\pi^0 \pi^0, \pi^0 \pi^0 \pi^0,$	$\pi^0 \pi^0$	24
$K_L \rightarrow \pi^+ \pi^- \pi^0$			9
$K_L \rightarrow \gamma \gamma$			0.04
K_L decays ($\bar{\gamma}$, charge)	$\pi^\pm e^\mp \nu, \pi^\pm \mu^\mp \nu, \pi^+ \pi^-$	$\pi^- e^+ \nu$.06
K_L decays ($\bar{\gamma}$, charge)	$\pi^\pm l^\mp \nu \gamma, \pi^\pm l^\mp \nu \pi^0, \pi^+ \pi^- \gamma$	$\pi^- e^+ \nu \gamma$	0.1
Other particle decays	e.g. $\Lambda \rightarrow \pi^0 n, \Sigma^+ \rightarrow \pi^0 p$	$\Lambda \rightarrow \pi^0 n$	0.03
Interactions	n, K_L , γ	$n \rightarrow \pi^0$	0.5
Accidentals	n, K_L , γ	n, K_L , γ	1.5
Total Background			35

SUMMARY

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$ offer unique opportunities to explore SM physics and search for non-SM effects.



E787→E949: heading below SM predictions

- E787 95-97 combined data still has one event!
- E787 -98 data will reach about 0.8×10^{-10}
- E949 aimed at $\leq 10^{-11}$ or 5-10 SM events

$$\underline{K_L^0 \rightarrow \pi^0 \nu \bar{\nu}}$$

A **direct** window into CP violation.

- Best way to determine η
 - Complementary to B system - compare results to search for new physics.

KOPIO

- Goal: 50 “SM” events
- Low background
- $\sim 7\%$ measurement of $Im\lambda_t$.
- Explore from 10^{-8} down to $\sim 10^{-12}$
(less than 1% of which is allowed by S.M.)

Any new physics will be unambiguous, unlike ϵ'/ϵ .

KOPIO: exploits special conditions at the AGS

- Proton intensity 10^{14} /pulse, micro-bunching
- Highly effective constraints and cross-checks
- Experience of recent AGS exps.

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ (E787): vetoes, electronics, analysis

$K^+ \rightarrow \pi^+ \mu e$ (E865) rates, calorimetry